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U.S. DEPARTMENT OF COMMERCE / National Bureau of Standards

An Experimental Technique for the Evaluation of Thermal Transient Effects on Piezoelectric Accelerometers

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FOREWORD

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AN EXPERIMENTAL METHOD FOR THE EVALUATION OF THERMAL-TRANSIENT EFFECTS ON PIEZOELECTRIC ACCELEROMETERS

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A simple, inexpensive method was developed for determining the effects of thermal transients on the zero output and sensitivity of piezoelectric accelerometers. Thermal transient stimuli are generated by an incandescent lamp and can be made to heat the top or side of the test accelerometer. Fourteen commercial accelerometers were tested using this technique. Zero shifts with magnitudes as high as 640 g_n* were observed. Zero shifts of up to 2% of full scale resulted from 1-s duration transients, and up to 7% of full scale from 15-s transients. These results were obtained at a radiation power density of 1.8 W/cm^2. No changes of accelerometer sensitivity exceeding experimental uncertainties were noted as a result of the thermal transients used.

Key words: accelerometer; performance characteristics; piezoelectric; test method; thermal radiation; thermal transient; zero shift.

1. Background

1.1 Needs for Thermal-Transient Test Method

1.1.1 Use of Piezoelectric Accelerometers

A piezoelectric accelerometer consists of a base structure, a loading mass, and a piezoelectric crystalline sensing element located between the mass and the base. Vibrational or shock acceleration applied to the accelerometer induces mechanical strains in the sensing element which generate electric charges in proportion to the applied acceleration. The sensing element may be a natural crystal, like quartz, or one of many proprietary piezoelectric materials.

Piezoelectric accelerometers are used extensively for measuring shock and vibrational motion in structures and components. These measurements may be used to demonstrate the ability of structures to withstand acceleration environments without damage, and to verify that components will operate with specified performance during and following exposure to shock or vibration conditions.

Accelerometers used for the measurement of blast-induced shock and vibration are also subjected to thermal-transient stimuli from the blast. Certain properties of piezoelectric accelerometers can

*1 g_n = approximately 9.8 m/s^2

cause them to generate spurious output signals in response to such thermal transients, leading to significant measurement errors.

1.1.2 Pyroelectricity and Differential Expansion of Components

Many piezoelectric crystalline materials are also pyroelectric [1],[2]*, that is, a change of temperature causes a change in the polarization charges in the material.

Pyroelectric output signals can result from a uniform or non-uniform distribution of thermal energy within the material. In addition, mechanical strain within the piezoelectric element, resulting from differential thermal expansion of the components of an accelerometer subjected to thermal transients, may generate spurious output signals.

In view of the transient nature of the thermal radiation stimulus experienced in blast conditions, non-uniform heating of the accelerometer so exposed is probable. The resultant output signal will thus include pyroelectrically generated charges and charges produced by changes in the mechanical loading of the crystal resulting from differential expansion of accelerometer components.

1.1.3 Consequences of the Unpredictability of Thermal-Transient Effects

Piezoelectric accelerometers are made in a large variety of models based on different design principals and constructed of various sensing-element, base, and case materials. The size of accelerometers varies as do connector locations. Furthermore, these accelerometers may be mounted in different ways on a variety of structures made of a variety of materials. The combination of these factors renders difficult and time-consuming the task of predicting analytically the effects of non-uniform heating, such as produced by a thermal transient, on the performance characteristics of a particular accelerometer structure.

Moreover, it is difficult to characterize the thermal radiation stimuli produced by blasts. The character of the blast (nuclear or non-nuclear) and its intensity, pulse shape and duration, spectral intensity, the location of the radiation measuring instruments, and the performance characteristics and calibration of these instruments may contribute to the uncertainty in any measured values of blast-induced thermal-transient radiation stimuli.

These limitations to an analytical prediction of the effects of thermal transients on the performance characteristics of piezoelectric accelerometers demonstrate a need for an experimental method of assessing these effects.

*Figures in brackets indicate literature references listed in section 6.

1.1.4 Test Method Requirements

An experimental method capable of realistic simulation of the blast-induced thermal-transient radiation environment to which the transducer may be exposed during measurement, while highly desirable, could be difficult and expensive to achieve because of the variety of possible blast parameters, the large amount of energy involved, and the problems involved in attempts to scale accurately blast-generated environments.

Accordingly, in agreement with the sponsoring agency, the task of developing a suitable thermal-transient radiation test method for screening accelerometers was provided the following guidelines:

1. The method is to be capable of identifying accelerometers that are least sensitive to reasonably short-duration thermal transients;
2. The method need not provide accurate simulation of blast-produced radiation environments;
3. The method is to be inexpensive to implement; and,
4. The method is to be simple to perform.

A thermal-transient test method does exist, but it is based on immersion and involves heat transfer by conduction only.

1.2 ANSI Method: Transient Temperature Effects on Piezoelectric Transducers

1.2.1 Description

In 1969, the American National Standards Institute published ANSI S2.11-1969, "American National Standard for the Selection of Calibrations and Tests for Electrical Transducers Used for Measuring Shock and Vibration"[3].

Section 8.6.2 of this standard deals with "Transient Temperature Effects on Piezoelectric Transducers." It is quoted below:

> "Pyroelectric outputs are generated in all piezoelectric transducers subjected to transient temperatures. The magnitude of the pyroelectric output depends upon the crystal material and the design of the transducer. Usually the predominant frequency of the pyroelectric output is significantly less than 1 Hz. Therefore, most of the pyroelectric output from the transducer is filtered out due to the low frequency characteristics of the amplifier. Accordingly, the pyroelectric output is dependent on the rate of the temperature change and on the characteristics of the amplifier as well as the characteristics of the transducer.
>
> "The pyroelectric test is performed using the type of amplifier normally used with the transducer. The transducer is attached to an aluminum block and both are quickly immersed in an ice bath or other liquid bath at a temperature 50°F [10°C] different

from room temperature. The block mass should be approximately ten times the mass of the transducer. The maximum amplifier output and the time from the start of the transient at which this maximum output is reached are measured on a dc oscilloscope. If the output reverses within the first two seconds and reaches a peak of opposite polarity, the magnitude and time of this peak are recorded also. For an accelerometer, the sensitivity is expressed in equivalent g/°F [g_n/°C] by dividing the maximum amplifier output by the product of the difference of the bath temperature and room temperature and the accelerometer sensitivity determined in 7.2. For a force transducer, the units are equivalent lbs/°F [N/°C]. The amplifier type is specified for which the pyroelectric sensitivity is applicable.

"For special applications using amplifiers having significantly different low frequency characteristic, the pyroelectric test is performed with the specific amplifier of intended use. Also, for applications in which the transient temperature rate is much different than that described by the above conditions, the test is performed by simulating the specific temperature environment."

1.2.2 Shortcomings of ANSI Method

The ANSI method described above is not satisfactory for evaluating effects of radiant-energy transients because it relies entirely on conductive heat transfer. Also, this method provides for the thermal input to be applied uniformly to all accelerometer surfaces except the base. In blast measurement situations, the radiant energy may impinge on the top or the side of the instrument; this condition is likely to induce differential expansion of various accelerometer components.

Further, a liquid-immersion method used to simulate the effects of short thermal transients is likely to result in splashing with consequent spurious acceleration signals. Finally, the assessment of a thermal-transient effect in terms of external temperature differentials may be misleading. Experience suggests that it is the radiant energy of the thermal transient absorbed by the accelerometer which most affects accelerometer performance. This energy input depends on the emissivity and conductivity of the components involved, factors not readily determined. However, if it is feasible to control or measure the radiant energy or radiant power level of the stimulus, repeatable test conditions may be achieved and verified.

Based on the considerations developed in this background section, a new, simple, and repeatable test method was developed for determining the effects of reproducible radiant-energy thermal transients on the performance of piezoelectric accelerometers.

2. Development of New Thermal-Transient Test Method

2.1 Test Method and Testing Conditions

2.1.1 Brief Description of Method

The method developed involves subjecting the test accelerometer to vibrational acceleration at the same time it is exposed to the thermal-transient stimulus created by a beam of radiant energy from a high-intensity incandescent lamp. A second accelerometer, shielded from the thermal stimulus but subjected to the same vibrational acceleration, measures the acceleration amplitude which both transducers experience. The thermal radiation can be made to impinge on whatever surface of the test accelerometer would be exposed during actual use in a blast situation, and there is little difficulty in simulating thermal transients as short as tens of milliseconds. The range of conditions can be extended beyond that used in this study by means of the use of sources of greater intensity and faster shutters.

The method is based on one previously developed which uses a beam of infrared radiant energy from a continuous-wave laser for investigating the effects of thermal transients on the performance characteristics of flush-diaphragm pressure transducers [4].

The high-intensity incandescent lamp selected is capable of a radiant-energy output somewhat less than that of the laser used previously, but its cost is substantially less than the cost of the laser.

2.1.2 Description of Experimental Apparatus

Figures 1 and 2 identify the major components of the experimental apparatus. Figure 1 shows the arrangement of components for tests with the accelerometer side exposed to the thermal radiation and also shows the photographic shutter used for most tests. Figure 2 shows the test arrangement for exposing the top of the accelerometer.

Both figures show a covered, aluminum, cup-like structure fastened to the amature of an electromagnetic vibration exciter. The reference accelerometer is mounted on the bottom of the cup, with its cable passing through a hole in the side wall of the cup. The accelerometer under test is mounted on the removable cover plate of the cup. The vibration exciter can be mounted so that the direction of vibration is aligned with the beam of incident radiation for irradiating the top surface of the test accelerometer, or perpendicular to the beam for irradiating the side of the test accelerometer. The metal framework surrounding the vibration exciter supports thermal shielding materials, the source of radiant heat energy, and a radiation sensor.

The thermal shield is a square plate of thermal insulating material about 20 cm x 20 cm supported by the framework to be about 5 cm above the cover plate on which the test accelerometer is mounted. A circular hole in the shield, about 8 cm in diameter, is concentric with the test accelerometer axis (figure 2). A sliding shutter of the same insulating material (not shown in figure 2) that normally covers this hole is withdrawn to permit the radiation to pass through the hole, or a commercial photographic shutter (as shown in figure 1) is centered over the hole. The shutter that has been used is self-cocking, opens to a clear diameter of 2.5 cm, and has speeds from 0.01 s to 1.0 s and bulb and time settings. It is necessary to protect the photographic shutter leaves from the thermal radiation by covering the shutter with an aluminum plate. Just before making an exposure, the plate is removed; it is replaced immediately afterwards.

A secondary radiation shield (shown in figure 2) is used to protect the cable of the reference accelerometer from the thermal radiation in tests in which the accelerometer top is exposed. The shield is not used in tests in which the accelerometer side is exposed as in this test configuration the cable exits from the side of the cup opposite the incoming radiation.

A 600-W quartz-bromine incandescent lamp mounted in a small aluminum reflector supplies the radiant energy. Energy output can be adjusted by means of a variable autotransformer fed from the laboratory a-c line. The lamp is mounted directly above the hole in the shield to irradiate the accelerometer under test. The lamp may also be swung laterally to position it directly above the absorption head of the radiation monitor (not shown in figures 1 and 2, but indicated in figure 3) to permit measurement of the radiant power output of the lamp.

The radiation emitted by the lamp is measured by a commercial broadband power meter described by the manufacturer as having a flat response over wavelengths of from 0.3 μm to 30 μm, and full-scale power readings of 1, 3, 10, 30, and 100 W. The meter consists of an absorption head and a control and read-out unit. The absorption head, which is mounted on the support framework, contains a coated metal disc. This disc absorbs the incident radiation over the specified range of wavelengths. The periphery of the disc is in intimate thermal contact with a finned, convection-cooled, heat sink in the absorption head, and the resultant radial heat flow from disc to sink is sensed by a concentric array of thermocouples connected to form a thermopile and mounted on the back surface of the disc. The voltage generated by the thermopile is amplified by the control unit and displayed on a meter in watts of radiant power.

To measure the radiant power, the sensing disc of the radiometer head is placed at the same distance from the radiation source as the test accelerometer top (or side) surface during thermal transient exposure. This distance, about 19 cm, is measured with a ruler to within an estimated ±2%.

The remainder of the apparatus consists of signal-conditioning and display devices for the accelerometer output signals, and a power amplifier and audio-frequency oscillator to drive the electromagnetic vibration exciter. A block diagram of the apparatus is shown in figure 3. A discussion of the signal-conditioning devices and their influence on test results is given in section 2.2

2.1.3 Selection of Test Conditions

The thermal-transient test method described in section 2.1.1 exposes the accelerometer under test to a transient of given duration and of given thermal radiant power, at the same time as it is subjected to vibrational acceleration. The applied acceleration, in turn, is of a given amplitude and at a given frequency. Initial experimental development of the new test method was concerned with the determinations of recommended values for each of the above test conditions. Considerations and experiments leading to the selection of particular test conditions will be described in the following sections.

2.1.3.1 Vibration Frequency

Selection of the vibration frequency at which the tests were to be run was based on the results of the experiment outlined below and some additional considerations derived from experience in evaluating accelerometer performance. Figure 4 shows the experimental results when a representative test accelerometer-charge amplifier system was subjected to a 1-W thermal transient at four vibration frequencies: 20, 50, 100, and 500 Hz. The observed differences in the responses at these four frequencies of about 5% are within the limits of experimental uncertainty. Since all test accelerometers have very high natural frequencies, their response should be the same over the range of frequencies of from 20 Hz to 500 Hz. Thus, any frequency in this range could presumably be selected as the test frequency.

Frequency limitations at the low end are dictated by the fact that the majority of commercial piezoelectric accelerometer-signal conditioner systems show varying amounts of roll-off at frequencies below about 20 Hz. In addition, the lower frequency limit of electronic voltmeters, including digital types, is typically about 50 Hz. These factors suggest that the test frequency be 50 Hz or higher. In regard to an upper test-frequency limit, it can be shown that the output of an accelerometer may be affected by the manner in which it is mounted and the material on which it is mounted and the material on which it is mounted. These effects are more pronounced at higher frequencies and, according to recent work, not significant below about 3000 Hz [5].

A convenient choice of frequency above 50 Hz and below 3000 Hz is 100 Hz. Accelerometer manufacturers generally use 100 Hz as their base, or reference frequency, when calibrating their accelerometers.

Further, 100 Hz provides adequate time resolution for examining the response of accelerometers to transient phenomena as short as the one-second test duration of the thermal-transient tests.

For the various reasons given above, 100 Hz was selected as the basic test frequency.

2.1.3.2 Vibration Amplitude

Selection of the vibration amplitude to be used for the thermal-transient test was based on the results of experiment. The accelerometer system used for the vibration frequency experiment (section 2.1.3.1) was also used to assess the effects of vibration amplitude. Experimental thermal-transient test data were obtained at 100 Hz and at ±2, ±4, ±6, ±8, ±10 g_n. A thermal power level of 1 W was used. Plots of accelerometer zero shift versus time for the five selected g_n values are similar in form to the plots of figure 4. Differences in response at these acceleration levels of less than 5% are within estimated experimental uncertainty.

As important consideration in the selection of the test vibration amplitude is the necessity of obtaining an adequate output from the transducer under test. Even with a charge sensitivity as low as 0.01 pC/g_n (near the minimum offered in commercial accelerometers) a ±10 g_n stimulus may produce an output of 100 mV from a commercial charge amplifier. This level of output is readily measured by a number of types of customary laboratory instruments, and this fact contributes to the selection of ±10 g_n as the test level. While a number of the earlier accelerometer evaluations were conducted at a level of ±5 g_n (10 g_n peak-to-peak), later tests use ±10 g_n (20 g_n peak-to-peak). This acceleration produces a higher output level (better signal-to-noise ratio) and is within the capability of most commercially available vibration exciters.

2.1.3.3 Radiation Power Level

Selection of the test radiation power level is based on the guideline requirement that the method be able to screen accelerometers to identify those experiencing large zero shifts on exposure to thermal transients.

Several factors were considered in the selection of the test radiation power level. A lower limit is the level for which the radiant energy is insufficient to produce any noticeable change in the output of a typical accelerometer. Upper limits are determined by cost-versus-capability constraints for the source of radiation, the shutter mechanism, and the radiation monitoring equipment.

The low cost of a 600-W quartz-bomine lamp and its capability of generating an adequate amount of radiant energy to produce a readily measurable effect on typical accelerometer output led to selection of this lamp as the radiant energy source. A broad-band radiometric power meter was already available in the laboratory, as was a photographic shutter capable of withstanding the radiation without malfunction. No effort was made to evaluate other sources of radiation, meters, or shutters.

The radiant energy impinging on the accelerometer (and shutter) is a function of lamp power and the distance from the lamp to the test specimen. A distance of 19 cm was selected to allow adequate working space between lamp and test specimen or shutter.

A series of tests was conducted with a variable-voltage transformer controlling the lamp electrical power as shown in figure 3. Figure 5, showing the effects of radiation power level on accelerometer zero shift, indicates a zero shift roughly proportional to power level over the range of power levels used. In this test, radiant power levels of 0.5, 1.0, 1.5, 2.0, and 2.5 W were used as measured by the radiometer. Based on the 1.9 cm-diameter of the radiometer absorbing disc, corresponding values of radiation power density are calculated to be 0.18, 0.35, 0.53, 0.70 and 0.88 W/cm^2, respectively. In this test, a charge amplifier was used to amplify the accelerometer signal, while the data shown in figure 6 for two other accelerometers tested at 5 W and 10 W were obtained with an electrometer amplifier. Again, the magnitudes of the zero shifts are roughly proportional to power level (at calculated power densities of 1.8 W/cm^2 and 3.6 W/cm^2, respectively) for each device during exposure. In all of these tests the thermal stimulus lasted 15 s. A power level of 5 W (power density 1.8 W/cm^2) was chosen for the thermal-transient test method because it produced an easily measurable effect on the output signal for a typical test accelerometer without inducing excessive thermal stress in, or otherwise damaging, the shutter.

2.1.3.4 Exposure Time

As indicated in section 1.1.4, for a variety of reasons the realistic simulation of blast-induced thermal-radiation environments is both difficult and expensive. A previously developed thermal-transient test procedure for pressure transducers involved transient stimuli lasting 50 s and 300 s [3]. The guidelines described earlier suggested that the test exposure duration be within an easily achievable range of times; experiment suggested a specific time from that range.

In exploratory tests conducted prior to making the decision to adopt 5 W as the standard power level, tests were conducted in which a beam of radiant energy was permitted to impinge on a representative test accelerometer over a variety of time intervals ranging from 1 s to 45 s and at a radiation power level of 1 W. In each experiment the path of the beam was normally blocked by a sliding shutter of thermally insulating material. The shutter was quickly removed manually and reinserted after the desired interval of time. Figure 7 shows the test results for this accelerometer, whose zero shift does not increase significantly for exposure times greater than 25 s. An exposure of

15 s produced a zero shift of about 75% of that attained after 25 s, but the choice of a 15-s exposure permitted more rapid testing since the energy absorbed by the test instrument dissipated more rapidly than with longer times. Tests with other accelerometers confirmed that a 15-s exposure produced easily measurable zero shifts with a minimum test time. This exposure time was easy to achieve with the manually operated sliding shutter. A variety of transducers was tested using the 15-s exposure and results are reported in section 3.3.

Subsequently, it became apparent that constraints imposed by the electrical time constants of the accelerometer-signal conditioner made it desirable to shorten the exposure time (section 3.2.1). Specifically, it was found that with short system time constants the electrical charge produced in the accelerometer by the thermal transient leaked off too rapidly for good measurements of zero shift. On the other hand, use of long system time constants tended to result in drifting output signals, making thermal-transient induced signals difficult to interpret. Accordingly, an exposure time of 1-s was selected, when practicable, to be combined with the selection of short time constants.

A photographic shutter replaced the sliding shutter for tests with thermal transients of 1-s duration. The majority of the test results reported in section 3 were obtained with this exposure time.

As indicated earlier, the sponsor agreed to the selection of specific test parameter values, as described above, and with the determination that the chosen values provided an adequate test method.

2.1.4 Sources of Error

2.1.4.1 Vibration Amplitude

The accuracy of calibration of the reference accelerometer at the frequency of test is estimated by the manufacturer as being within limits of uncertainty of ±2% of the reading up to 1 kHz (traceable to NBS). Test and reference accelerometers are mounted on surfaces parallel to each other within ±1 degree, and perpendicular to the direction of vibration within the same tolerance. The estimated uncertainty in the acceleration applied to the test accelerometer that may be charged to angular misalignment is less than ±0.01%, negligible compared to errors from other sources. The charge amplifier used as signal conditioner for the reference accelerometer showed a maximum deviation of -1.3% from nominal output values at 100 Hz. The digital voltmeter used to measure the output of the reference accelerometer system has an estimated uncertainty of ±0.1%. Based on the individual uncertainties, the uncertainty of the knowledge of the applied vibrational acceleration amplitude is estimated to be within about -3.4%, +0.8% of the reading at test values.

2.1.4.2 Output of Test Accelerometer

The output of the test accelerometer was amplified with the aid of a charge-sensitive amplifier or an electrometer amplifier and displayed on the screen of an oscilloscope.

The charge-sensitive amplifier used showed a maximum deviation of +2.0%, -2.4% from the nominal output values at 100 Hz, over the ranges used. The gain of the electrometer amplifier at 100 Hz has an estimated uncertainty of ±2% of full scale. Deflection sensitivity of the oscilloscope enters into the error considerations since the thermally induced zero shift is scaled with reference to the displayed vibration amplitude from the reference accelerometer-digital voltmeter system. Hence the output of the test accelerometer is influenced by amplifier uncertainties and the ability of the test operator to measure deflections on the oscilloscope screen, estimated to be ±3% of the signal amplitude for a typical operator. The total uncertainty of the test accelerometer output values is estimated at about ±5% of the reading.

2.1.4.3 Radiant Power Level

The radiometer used is described by its manufacturer as having an accuracy of ±5%, of full scale. The area of irradiation (or the area resulting when the surface of the accelerometer exposed to the radiation is projected onto a plane normal to the radiation beam axis) was calculated from scale measurements and is estimated to have an uncertainty of ±5%. Consequently, the value of the radiant power density (W/cm^2) is estimated to be known to better than ±10% of full scale.

The repeatability of radiant power-level measurements is limited by the resolution of the meter scale, approximately ±1% of full scale.

2.1.4.4 Error Summary

In a typical measurement, the uncertainty in the knowledge of the radiant power level is estimated at ±10%. The resultant zero shift of a test accelerometer is estimated to be known within an uncertainty of approximately ±5% (section 2.1.4.2) in the absence of time-constant sources of error. These errors will be treated in more detail in section 3.2.

2.2 Signal Conditioning Considerations

2.2.1 Charge-Sensitive Amplifiers

It may be useful to review briefly some of the signal conditioning considerations pertaining to piezoelectric accelerometers. The output of piezoelectric accelerometers can be amplified either by charge or voltage amplifiers. The charge-sensitive amplifier (also referred to simply as "charge amplifier") converts an input in the form of a charge, from the piezoelectric transducer, to a voltage signal. Most charge amplifiers consist of two sections: a charge converter and a voltage amplifier. The gain of the amplification section is frequently adjustable so that the transducer can produce a conveniently scaled output.

In order to achieve stable operation, most charge amplifiers make use of a feedback resistor connected between the input and the output of the amplifier section, and in parallel with the feedback capacitor. The time constant of the system is then defined by the R-C time constant of the feedback resistance-feedback capacitance combination. Often several switch-selectable feedback resistors are provided allowing the operator to choose the desired time constant by switching the proper resistor into the circuit. The feedback network which permits selectable gain will also control the time constant. This arrangement may cause measurement errors in the case of low-frequency phenomena.

The main advantage of the charge amplifier is that the system sensitivity is unaffected by the length of cable between the transducer and the charge amplifier, although the noise level increases with an increase in cable length. With long cables the charge amplifier is particularly sensitive to spurious signals generated in the cable.

The effect of the charge-amplifier time constant on accelerometer system output during a thermal-transient test is shown in figure 8. Both maximum output amplitudes and the time over which the output remains elevated are controlled by the time constant.

Medium and long time-constant settings are very difficult to use in tests with most piezoelectric accelerometers because of the very large, random drifts in output caused by minute accelerometer temperature changes, cable flexing, small vibrations, etc. Such time constants are rarely used in field measurements. Measurements with long time constants are generally used only for quasi-static calibration of transducers with low internal leakage, such as quartz-crystal pressure transducers.

In view of these limitations, a useful experimental technique should employ a short time-constant setting of the charge amplifier, unless, because of the interaction between time constant and range setting, the longest available time constant is less than the duration of the test stimulus. It is important to realize the thermal-transient test data obtained at short time constant settings will not be representative of accelerometer system response measured with long time-constant settings of the charge amplifier.

2.2.2 Voltage Amplifiers

Special-purpose, impedance-matching voltage amplifiers are frequently used with piezoelectric transducers. The amplifiers have extremely high input impedances to minimize the unavoidable effects of low-frequency roll off due to a short time constant.

The voltage amplifier is perhaps easier and simpler to use than the charge amplifier. Because of its simplicity, it is the lower in cost of the two classes of signal-conditioning amplifiers. The voltage amplifier also has a higher frequency-response capability than the charge amplifier.

A disadvantage of the voltage amplifier is the fact that voltage amplifiers with long time constants are difficult to obtain. Further, when used with piezoelectric transducers the signal available at the amplifier input terminals is inversely proportional to transducer and cable capacitance, and therefore, in effect, to cable length.

On the other hand, the voltage amplifier does not suffer from one of the basic constraints in the design of the charge amplifier, the change in time constant with range. This feature makes it less difficult to compare accelerometers of widely differing sensitivities using voltage amplifiers.

The voltage amplifier has a time constant determined by the total capacitance (transducer, cable, amplifier input) as seen by the amplifier, and the total resistance across the input. The electrometer amplifier has a number of voltage ranges, as well as a control for changing its input resistance settings of up to $10^{14}\Omega$ are in decade ranges. The effects of input resistance on accelerometer zero-shift were investigated and the results are shown in figures 9 and 10, for two different accelerometers. The zero-shift observed is greater for larger values of input resistance (and therefore longer instrument time constants).

Changes in voltage range settings of the electrometer amplifier were found to have no effect on the zero-shift observed. An electrometer amplifier therefore makes it possible to compare the thermal-transient responses of different accelerometers using the same electrical time constant, through proper setting fo the input resistance control of the electrometer.

2.2.3 Use of Electrical Filters

To reduce the problems of instrument drift, some users insert a simple, high-pass filter in each piezoelectric accelerometer instrumentation channel. The amplitude-frequency response characteristics of a typical filter shows a drop of 5% at 2 Hz. To investigate the effects of such a filter on the thermal-transient response of the accelerometer, tests were conducted with the filter inserted between the charge amplifier or electrometer amplifier and the oscilloscope. The filter used to provide the desired response consists of a 0.24-μF capacitor and 1.0-MΩ resistor. Since the input resistance of the vertical amplifier of the oscilloscope used is 1.0 MΩ, the addition of a 0 24-μF series capacitor at the amplifier input is sufficient to provide the desired high-pass filtering. The time-constant of this filter is 0.24 s. For tests in which this filtering was not used, the output signal from the amplifier was directly coupled to the oscilloscope.

3. Thermal-Transient Tests on Fourteen Accelerometers

3.1 Test Results Using One-Second Exposure

Fourteen accelerometers, two each of seven different models, were received from the sponsoring agency for testing. Five of the models are piezoelectric ceramic types (three of shear design, and two of single-ended compression design), one model contains a piezoelectric quartz crystal, and the remaining model has a piezoresistive strain-gage sensor. Table 1 lists the characteristics of the accelerometers as provided by their manufacturers. As indicated earlier, comparison tests of thermal-transient effects on the performance of various accelerometers could best be accomplished through the use of electrometer amplifiers as there would be no gain-time constant constraints. Since the types of accelerometers tested are frequently used in conjunction with charge amplifiers, however, tests were conducted with charge amplifiers as well.

In the tests, each accelerometer was subjected to a radiant power density of 1.8 W/cm^2 for 1 s. The acceleration level applied during the test was 20 g_n peak-to-peak at 100 Hz. Four different circuit configurations were used: (1) charge amplifier directly coupled to the oscilloscope; (2) charge amplifier capacitively coupled to the oscilloscope; (3) electrometer directly coupled to the oscilloscope; and (4) electrometer capacitively coupled to the oscilloscope. High-pass filtering due to capactive coupling is discussed in section 2.2.3. Figures 11, 12, and 13 show results from the 1-s exposure tests. Figure 13 shows the effect on accelerometer output of each of the circuit configurations listed above. Tables 2 through 5 contain tabulated test results.

Test results from transducer evaluations are generally expressed as percentages of the full-scale range of the transducer. Most transducers are used for measurement of physical quantities with amplitudes near the full-scale range. In these cases, transducer errors or deviations expressed as percentages of full scale convey a useful measure of the quality of the measurement. This may not always be true for piezo-electric accelerometers.

In the case of many piezoelectric accelerometers, particularly those used for shock measurements, the full-scale design range of the accelerometer is very high. Among the accelerometers evaluated by the thermal-transient test, the lowest full-scale range was ±2000 g_n; the highest +100,000 g_n, -20,000 g_n. Measurements of very high accelera-tion levels may not really be very meaningful. Errors may result from attachment constraints, inhomogeneities in materials, lack of adequate frequency response to reproduce correctly transient accelerations, and other factors. The full-scale range of such an instrument is primarily chosen to give adequate margins of safety against overloading. Actual acceleration amplitudes measured with such accelerometers may not exceed one-tenth of their full-scale range.

It appears then that reporting accelerometer characteristics only as a percentage of a (possibly quite unrealistic) full-scale range may ultimately lead to a misleadingly optimistic interpretation of experimental measurements. For this reason, thermal-transient zero-shift values obtained in the tests are expressed in this report in terms of the change in acceleration corresponding to the zero shift (in units of g_n).

3.1.1 Tests with Charge Amplifier

Thermal-transient test results using the charge amplifier are compiled in tables 2 and 3. Results of tests on four accelerometers having their top surface exposed to a thermal transient are shown in figure 11 and figures 13-c and -d. The character of the response differs considerably for different accelerometers, as it does for top and side exposures. The test results compiled in table 2 were obtained with the charge amplifier directly coupled to the oscilloscope used to display the thermal-transient response of the accelerometer. Table 3 contains the results from tests using capacitive coupling between the charge amplifier and the oscilloscope, equivalent to the introduction of a high-pass filter into the system.

With the charge amplifier directly coupled to the oscilloscope, the zero shifts observed ranged from +640 g_n (B-1) to +2.3 g_n (E-1) for top exposure, and from +280 g_n (B-1) to +1.4 g_n (E-1) for side exposure. With the charge amplifier capacitively coupled to the oscilloscope, the zero shifts displayed were smaller because of the high-pass filtering. The exposure values ranged from +80 g_n (B-1) to -0.17 g_n (C-2). Side exposure values ranged from +22 g_n (B-1) to -0.06 g_n (C-2). The effects of the high-pass filter are discussed in more detail in section 3.3.2 below.

3.1.2 Tests with Voltage Amplifier (Electrometer)

Thermal-transient test results with the electrometer amplifier are compiled in tables 4 and 5. Figure 12 shows the thermal-transient responses of two different accelerometers when top or side surfaces are irradiated. In these cases the high-pass filter was used (section 3.3.2). Figures 13-a and -b also show accelerometer responses using the electrometer. In the case of the one-s tests the electrometer input resistance was $10^{10}\Omega$.

With the electrometer amplifier directly coupled to the oscilloscope, the zero shift observed ranged from +365 g_n (B-1) to +2.6 g_n (E-2) for the top exposure, and from +90 g_n (B-1, B-2) to +1.5 g_n (E-1) for side exposure. With capacitive coupling, the zero shifts observed ranged from +53 g_n (B-1) to 0.17 g_n (C-1) for top exposure, and from +25 g_n (B-1) to -0.09 g_n (C-1) for side exposure.

3.2 Test Results Using Fifteen-Second Exposure.

As indicated in section 3.1.3.4, initial experiments in the development of the thermal-transient test method suggested a 15-s exposure as a reasonable test value. Experimental data were obtained at this exposure duration for all accelerometers, using the electrometer amplifier directly coupled to the oscilloscope. The results are compiled in table 6. Some accelerometer responses are shown in figure 14. The input resistance for these tests was $10^9 \Omega$, and the radiant energy density was 1.8 W/cm^2, applied to the top surface only in these tests.

Each accelerometer model appears to have a distinctive pattern of zero shift, with slight variations between different accelerometers of the same model. The maximum zero shifts ranged from +2.4 g_n (E-2) to +350 g_n (B-1).

3.3 Discussion of Test Results

The test results indicated general patterns of behavior in thermal-transient environments for the types of accelerometers sampled; however, a larger sampling of accelerometers than the limited one available for these tests would be required for definitive predictions about the behavior of other accelerometers of these types.

During some of these tests, attempts were made to measure changes in sensitivity in addition to zero shift. Small changes were observed in some cases, but results were not consistent. It appears that a maximum shift in sensitivity of about 3% may be expected to occur after a 15-s exposure at 2.5 W (radiant energy density of 0.88 W/cm^2) and that somewhat smaller changes may be expected at the lower power levels. The effects of such sensitivity changes during actual vibration measurements are negligible in comparison with the predicted zero shifts observed during these tests.

3.3.1 Top and Side Exposure

Table 7 gives the exposed area in cm^2 for each accelerometer type tested, for both top and side exposures. These areas are the projected areas which intercept the incoming thermal radiation and are calculated from measurement of accelerometer dimensions. The table also gives calculated values of radiant power intercepted by the projected areas for a radiant power density of 1.8 W/cm^2.

The experimental results given in tables 2 and 4 (1-s exposure, use of charge amplifier or electrometer amplifier directly coupled to oscilloscope) show that accelerometer types B and D exhibit significantly greater zero shift when the accelerometer top is exposed than when the side is exposed. Accelerometer type E shows a larger zero shift when its top surface is exposed to radiation, possibly because its exposed top area is almost four times as large as the exposed side area. For accelerometers B and D, the respective areas are almost equal. Accelerometer types A and F show a larger zero shift when their sides are exposed; the side areas of these types are considerably larger than the top areas. In the case of the other accelerometer types no clearly detectable differences were found between the effects of exposing the two surfaces.

3.3.2 System Time Constants and the Effects of High-Pass Filters

As described earlier, the accelerometers were tested in four different circuit configurations: charge amplifier with direct and capacitive (i.e., with high-pass filter at the input of the monitoring oscilloscope) coupling and electrometer with direct and capacitive coupling. The data from these tests, using a 1-s thermal radiation exposure, are shown in tables 2 through 4. These tables also show the values of the time constant used for each measurement. In the case of the charge amplifier, the value of time constant given is that obtained from the manufacturer's instruction manual, which tabulates time-constant values for all combinations of range and time-constant switch settings.

The piezoelectric accelerometer can be assumed to be an instantly responding source of charges with extremely high internal resistance. When used with the electrometer, which is a voltage-sensing device, the accelerometer can be assumed to be an instantly responding voltage generator in series with a capacitance. This series capacitance is the sum of the accelerometer and cable capacitances. The capacitance-resistance network formed by this series capacitance and the electrometer's input resistance acts as a high-pass filter with a specific time constant, listed in the appropriate tables under the heading "Electrometer Time Constant."

Since some laboratories use an additional R-C high-pass filter in all piezoelectric accelerometer channels to reduce drift caused by the generation of spurious charges, our tests also included measurements using such a filter with a sinusoidal amplitude-frequency response down 5% at 2 Hz and a corresponding time constant calculated to be 0.24 s.

A series of measurements of the equivalent time constant was made using the various circuit configurations — charge amplifier with direct and capacitive coupling and electrometer with direct and capacitive coupling. A step voltage from a function generator was fed into the charge amplifier's calibrating input or into the electrometer, and the resulting signal was displayed on the oscilloscope and photographed. The time constant was estimated from the photograph as the time required for the signal to drop to $^1/e$ (36.8%) of its initial value. Some of the time constants for the electrometer directly coupled are too long to be determined in the above manner with the equipment available.

The tests were made with the sensitivity, range, input resistance, and time-constant settings that had been used with the various accelerometers. The voltage of the function generator was set so that the output signal displayed on the oscilloscope approximated the zero-shift observed for the accelerometer being simulated.

Values for the time constant with capacitive coupling ranged from 0.20 s to 0.25 s with a scaling accuracy estimated as ±0.05 s. This agrees well with the calculated value of 0.24 s. Time constants using the charge amplifier with direct coupling measured 10.2 s for the simulated type A accelerometer (calculated time constant 10 s); 6.5, 5.7, and 7.5 s for types B, C, and D respectively (calculated time constant 5 s) and 3 s for types E and F (calculated time constants 2 s). Scaling accuracy for these measurements is estimated at ±0.5 s.

The data from the thermal-transient tests were analyzed on the assumption that the thermal-transient input to the accelerometer and the resulting output are ramp functions. The rise time of this ramp is assumed equal to the time interval from the initiation of the transient to the time of maximum output observed. This assumption is based on the appearance of the output signal (figures 11-14) and experimental data taken at longer exposures (figures 7 and 8) which indicate that the output signal appears proportionately greater at these exposures. The 1-s thermal-transient stimulus cannot be considered either a step function or an impulse because shutter opening and closing times are significant compared to 1 s. Assumption of an exponential rise time would have increased mathematical complexity. The ramp function was chosen as the most practical representation of the thermal-transient-generated output signal, and the results of data normalization (table 8) appear to justify this choice.

A theoretical study was undertaken of the output resulting from the application of a ramp function to a series combination of two R-C high-pass filters. The filters were chosen to represent the capacitance of the accelerometer and the input resistance of the electrometer, followed by the coupling capacitance, and the input resistance of the oscilloscope. Alternately, they can represent the charge-amplifier time constant, followed by the coupling capacitance-oscilloscope input resistance time constant. The other two test conditions which do not use the oscilloscope input high-pass filter were also studied, being represented by a ramp function applied to a single R-C high-pass filter. In the studies, parameters considered were the ratio (Q) of ramp rise time (T) to filter time constant (RC), and the ratio (m) of the time constants of the two filters $(RC)_1$, and $(RC)_2$, when these were used.

It can be shown for the case of the single high-pass filter that the maximum output signal reached at time T is proportional to $\frac{1-e^{-Q}}{Q}$. The signal decays exponentially after this. In the case of two high-pass filters, the output signal at time T is proportional to $\frac{1}{Q}\left(\frac{m}{1-m}\right)\left(e^{-1}-e^{\frac{\cdot 1}{m}}\right)$. With the aid of these relations, the data from the 1-s test on accelerometers A-1, B-1, C-1, E-1, and F-1 were normalized (for comparison purposes) to represent the actual transducer output with an assumed infinite time constant. The results are given in table 8 and show reasonable agreement for four of the six accelerometers tested (B-1, D-1, E-1, and F-1). In the case of A-1, it should be noted that the original test data showed a large, continuing, negative drift for measurements in which no high-pass filter was used (precisely the situation for which the filters are required in actual measurement systems). The direction of the observed drift was consistent with the large discrepancy observed. Figure 11-a shows this drift. The discrepancy in the data from accelerometer C-1 was noticeable, but smaller than that for A-1. The former type of accelerometer also showed some negative drift, prior to the thermal-transient input. Figure 13-a shows this drift for accelerometer C-2.

3.3.3 Relation of Test Results to Accelerometer Features

The zero shift exhibited by some of the accelerometers tested is substantial; but there is no measurably significant change in sensitivity, as evidenced by the nearly constant signal amplitude observed over each measurement. Zero shift varied considerably both in amplitude and direction among the different models of accelerometers. These variations are believed to result from differences of geometry (shape, size, and placement of electrical connectors and fastening hardware), design (shear or compression type, materials), and electrical characteristics (capacitance, leakage resistance) of the accelerometers. The effects of time constants of the ancillary electronics are discussed in 2.3.2.

Accelerometers B-1 and B-2 show the largest radiation-induced zero shifts (positive direction). Accelerometers E-1 and E-2 also show a positive zero shift (but of much smaller magnitude). These two are the only types of transducer tested to exhibit positive shift; both are of shear-type design, with the piezoelectric crystal serving as both sensor and seismic mass. Accelerometer type B has a massive metallic center post closely coupled to a substantial outside case. The design is such that any heat energy impinging on top or side would be expected to diffuse rapidly into the round center post (to which the crystal is attached and with which it is concentric). Consequent lateral expansion of the center post resulting in stress on the piezoelement appears likely.

Accelerometer type E has a much smaller center post than type B and had massive case walls; furthermore, when the instrument is mounted for measurements, the piezoelement is actually below the mounting surface. This design should provide good shielding from thermal radiation consistent with the small zero shifts observed.

Accelerometer type D is also a shear design. The center post in this design is less massive than in type B, and is pierced for the mounting screw. Walls are moderately thick, and the connector block is massive. A reasonable prediction of the behavior of this design when exposed to a thermal transient is that a portion of the heat energy would be transmitted to the center post resulting in expansion of the post and consequent application of stress to the piezoelement. On this basis, the zero shift for this instrument should be greater than that for type B. There is no satisfactory explanation of the observed negative direction of zero shift.

Accelerometer types A, C, F (single-ended compression types) all show similar negative zero shifts, with F (having a quartz sensing element) showing the smallest shift. In the single-ended compression design the circular sensing-element disc is loaded with a circular plate mass on top. Both elements are pierced with a center hole through which a threaded stud protrudes from the instrument base. A nut engages the top of the stud and compresses mass and sensing element; a case surrounds the elements and is attached to the base. This design should result in small zero shifts being induced by thermal irradiation because of the isolation between case and sensing element. The large zero shift observed for type A has not been explained, but it should be noted that these instruments showed a considerable negative drift even before they were exposed to thermal radiation in the test. Type C also showed a similar negative drift, but of smaller magnitude.

When irradiated for 15 seconds, accelerometer types D and G and one of the type F accelerometers displayed a sharp reversal of zero-shift direction upon closing of the shutter. Addition of the high-pass filter to the signal conditioning circuit greatly reduced the zero shift in all cases (in come cases almost to zero). These observations show that the thermal-transient zero shift in piezoelectric accelerometers is essentially a low-frequency phenomenon, and that the resulting effects can be controlled with selection of the proper high-pass filter.

Whether an accelerometer is affected more by irradiation impinging on its side or on its top surface varies with the different accelerometer models. Most of the accelerometers (five of the seven types) showed greater zero shifts when the surface having the larger area was irradiated. But no definite correlation between surface area and zero-shift amplitude could be established.

4. Conclusions

Many users of piezoelectric accelerometers may be unaware of the measurement errors that can result from the use of these accelerometers in thermal-transient environments. Because it has been shown that the zero shift due to thermal transients may vary widely among the different models of accelerometers and because there is no simple means of predicting the zero shift, it is recommended that tests be performed to determine such shifts for accelerometers that are to operate under conditions in which thermal-transients are present.

The thermal-transient test method reported here for piezoelectric accelerometers is simple, inexpensive, and well suited for such tests. Adjustability of the duration or intensity of the thermal transient is possible over a wide range of values and adaptation of the system for irradiating various accelerometer surfaces is possible. The use of radiant energy to provide the thermal transient simulates the conditions of field use for blast measurements more closely than the previously used method of ANSI S2.11-1969 [3].

5. Recommendations

Recommended is an investigation of the adaptability of the test method described for the testing of other types of transducers for thermal-transient effects. In particular, it it felt that this method would be much less expensive than the laser method referenced earlier for measuring thermal-transient effects in pressure transducers.

6. References

[1] Cady, W. G., Chapter 29-Pyroelectricity, Book, Piezoelectricity, pp. 699-712 (McGraw-Hill Book Co. Inc., New York, NY, 1946 and Dover Publishers, Inc., New York, NY, 1964).

[2] Dranetz, A. I., and Orlacchio, A. W., Chapter 16-Piezoelectric and Piezoresistive Pickups, Book, Shock and Vibration Handbook, Ed. C. M. Harris and C. E. Crede, (McGraw-Hill Book Co. Inc., New York, NY, 1961).

[3] "American National Standard for the Selection and Calibrations and Tests for Electrical Transducers Used for Measuring Shock and Vibration", ANSI S2.11-1969 (American National Standards Institute, New York, NY, 1969).

[4] Lederer, P. S., and Hilten, J. S., A Laser Technique for Investigating the Effects of Thermal Transients on Pressure Transducer Performance Characteristics, NBS Tech. Note 723 (May 1972).

[5] Koyanagi, R. S., Pollard, J. D., and Ramboz, J. D., A Systematic Study of Vibration Standards-Mounting Effects, NBSIR 73-291 (September 1973).

Table 1

Test Accelerometer Characteristics
(Supplied by Manufacturers)

Accelerometer	Capacitance Accelerometer & Cable)	Sensitivity	Design Type	Range	Natural Frequency Mounted
	pF	pC/g_n		g_n* 0 to peak	kHz
A-1	2902	13.1	SEC**	±2,000	37
A-2	2886	13.1	SEC	±2,000	37
B-1	282	0.0286	Shear	+100,000 -20,000	80
B-2	287	0.289	Shear	+100,000 -20,000	80
C-1	2358	65.0	SEC	±10,000	29
C-2	2062	54.1	SEC	±10,000	29
D-1	563	0.161	Shear	±20,000	100
D-2	572	0.164	Shear	±20,000	100
E-1	253	0.127	Shear	±20,000	125
E-2	242	0.129	Shear	±20,000	125
F-1	239	0.331	SEC (Quartz)	+100,000 -20,000	60
F-2	239	0.303	SEC (Quartz)	+100,000 -20,000	60
G-1	- -	5.84μV/g_n	Piezoresistive	±20,000	90
G-2	- -	5.84μV/g_n	Piezoresistive	±20,000	90

* 1.00 g_n = approximately 9.8 m/s^2.

** Single-Ended Compression

Table 2

Thermal-Transient Effects on Accelerometers
For One-Second Exposure Using
Charge Amplifier Directly Coupled to Oscilloscope

Accelerometer	Charge Amplifier Time Constant(s)	Maximum Zero Shift (g_n)	
		Top Irradiated	Side Irradiated
A-1	10	-25. **	-39. **
A-2	10	-39. **	-44. **
B-1	5	+640.	+280.
B-2	5	+340.	+150.
C-1	5	-4.6	-4.0
C-2	5	-6.1	-4.0
D-1	5	-31.	-5.0
D-2	5	-24.	-4.0
E-1	2	+2.3	+1.4
E-2	2	+2.5	+1.9
F-1	2	-8.3	-16.
F-2	2	-3.3	-7.0
G-1	*	-2.4	-5.0
G-2	*	-4.0	-5.5

* Piezoresistive transducer, no signal conditioner used

** Considerable negative drift before radiation exposure

Table 3

Thermal-Transient Effects on Accelerometers
For One-Second Exposure Using
Charge Amplifier-Capacitively Coupled to Oscilloscope

Accelerometer	Charge Amplifier Time Constant(s)	Maximum Zero Shift (g_n)	
		Top Irradiated	Side Irradiated
A-1	10	-0.57	-3.0
A-2	10	-0.57	-2.9
B-1	5	+80.	+22.
B-2	5	+57.	+12.
C-1	5	-0.23	-0.15
C-2	5	-0.17	-0.06
D-1	5	-8.6	-1.5
D-2	5	-7.0	-1.1
E-1	2	+0.46	<0.1
E-2	2	+0.47	+0.14
F-1	2	-3.0	-4.2
F-2	2	-1.3	-2.5
G-1	*	-1.0	-2.0
G-2	*	-1.6	-1.8

* Piezoresistive transducer, no signal conditioner used

Table 4

Thermal-Transient Effects on Accelerometers
For One-Second Exposure Using
Electrometer Amplifier Directly Coupled to Oscilloscope

Acceler-ometer	Electrometer Time Constant(s)	Maximum Zero Shift (g_n)	
		Top Irradiated	Side Irradiated
A-1	29.	-37. *	-60.
A-2	29.	-37. *	-48.
B-1	2.8	+365.	+90.
B-2	2.9	+210.	+90.
C-1	24.	-10.	-11.
C-2	21.	-12.	-9.0
D-1	5.6	-27.	-5.0
D-2	5.7	-46.	-4.3
E-1	2.5	+2.7	+1.5
E-2	2.4	+2.6	+2.5
F-1	2.4	-7.5	-2.6
F-2	2.4	-3.3	-7.6

* Considerable negative drift before radiation exposure

Table 5

Thermal-Transient Effects on Accelerometers
For One-Second Exposure Using
Electrometer Amplifier Capacitively Coupled to Oscilloscope

Accelerometer	Electrometer Time Constant(s)	Maximum Zero Shift (g_n)	
		Top	Side
A-1	29.	-0.54	-2.7
A-2	29.	-0.57	-2.9
B-1	2.8	+53.	+25.
B-2	2.9	+30.	+8.6
C-1	24.	-0.17	-0.09
C-2	21.	-0.27	-0.13
D-1	5.6	-7.6	-1.4
D-2	5.7	-8.8	-0.87
E-1	2.5	+0.50	+0.20
E-2	2.4	-0.57	+0.19
F-1	2.4	-2.6	-8.0
F-2	2.4	-1.1	-2.5

Table 6

Thermal-Transient Effects on Accelerometers
For Fifteen-Second Exposure Using
Electrometer Amplifier Directly Coupled to Oscilloscope

Accelerometer	Electrometer Time Constant(s)	Maximum Zero Shift (g_n)	Time Interval to Peak Output(s)
A-1	2.9	-130	20
A-2	2.9	-120	20
B-1	0.28	+350	5
B-2	0.29	+210	5
C-1	2.4	-39	19
C-2	2.1	-45	18
D-1	0.56	-160 **	1
		+15	16
D-2	0.57	-180	1
		+19	16
E-1	0.25	+2.6	15
E-2	0.24	+2.4	5
F-1	0.24	-4.2	1
F-2	0.24	-2.1	1
		+3.3	16
G-1	*	-30	15
G-2	*	-11	2

* Piezoresistive transducer, no signal conditioner used

** Positive and negative peaks observed

Table 7

Thermal Power Input Levels in Accelerometer Tests, Power Density = 1.8 W/cm^2

Accelerometer Type	Exposed Area (cm^2)		Radiant Power Incident on Accelerometer (W)	
	Top	Side	Top	Side
A	2.1	3.1	3.8	5.4
B	1.8	1.7	3.1	3.0
C	2.1	3.1	3.8	5.4
D	1.0	0.67	1.5	1.2
E	0.54	0.16	0.95	0.30
F	0.91	1.5	1.6	2.6
G	1.4	0.61	2.4	0.81

Table 8

Test Oata Normalized on the Basis of System
Time Constants
One-Second Exposure

Accelerometer	Time Constant(s) $(RC)_1$ Electrometer	Time Constant(s) $(RC)_1$ Charge Amplifier	Time Constant(s) $(RC)_2$ High-Pass Filter	$m=\frac{(RC)_2}{(RC)_1}$	Ramp Rise Time T(s)*	$Q=\frac{T}{(RC)_1}$	Computed Amplitude Ratio (see Note)	Maximum Test Output (g_n)	Normalized Output (g_n)
A-1	29.		0.24	0.0083	1.0	0.034	0.23	-0.54	-2.3
	29.				35.	1.2	0.58	-37.	-64.
		10	0.24	0.024	1.0	0.10	0.22	-0.57	-2.6
		10			25.	2.5	0.37	-25.	-68.
B-1	2.9		0.24	0.083	2.0	0.7	0.094	+53.4	+570.
	2.9				4.0	1.4	0.54	+365.	+680.
		5	0.24	0.048	2.0	0.40	0.11	+80.	+730.
		5			4.0	0.80	0.69	+640.	+930.
C-1	24.		0.24	0.010	4.0	0.17	0.056	-0.17	-3.0
	24.				18.	0.75	0.70	-10.2	-15.
		5	0.24	0.048	4.0	0.80	0.053	-0.23	-4.3
		5			13.	2.6	0.36	-4.6	-13.
0-1	5.7		0.24	0.042	0.7	0.12	0.30	-7.6	-25.
	5.7				1.0	0.18	0.92	-27.4	-30.
		5	0.24	0.048	0.7	0.14	0.30	-8.6	-29.
		5			1.0	0.20	0.91	-31.0	-34.
E-1	2.5		0.24	0.096	1.0	0.40	0.18	+0.50	+2.8
	2.5				2.0	0.80	0.69	+2.7	+3.9
		2	0.24	0.12	1.0	0.50	0.18	+0.46	+2.6
		2			2.0	1.0	0.63	+2.3	+3.7
F-1	2.4		0.24	0.10	0.8	0.33	0.29	-2.6	-9.0
	2.4				1.0	0.42	0.82	-7.5	-9.1
		2	0.24	0.12	0.8	0.40	0.23	-3.0	-13.
		2			1.0	0.50	0.79	-8.3	-11.

NOTE

Amplitude ratio for two time-constant systems computed from $\frac{1}{Q}\left(\frac{m}{1-m}\right)\left(e^{-1} - e^{-\frac{1}{m}}\right)$

Amplitude ratio for single time-constant systems computed from $\frac{1-e^{-Q}}{Q}$

*from test data

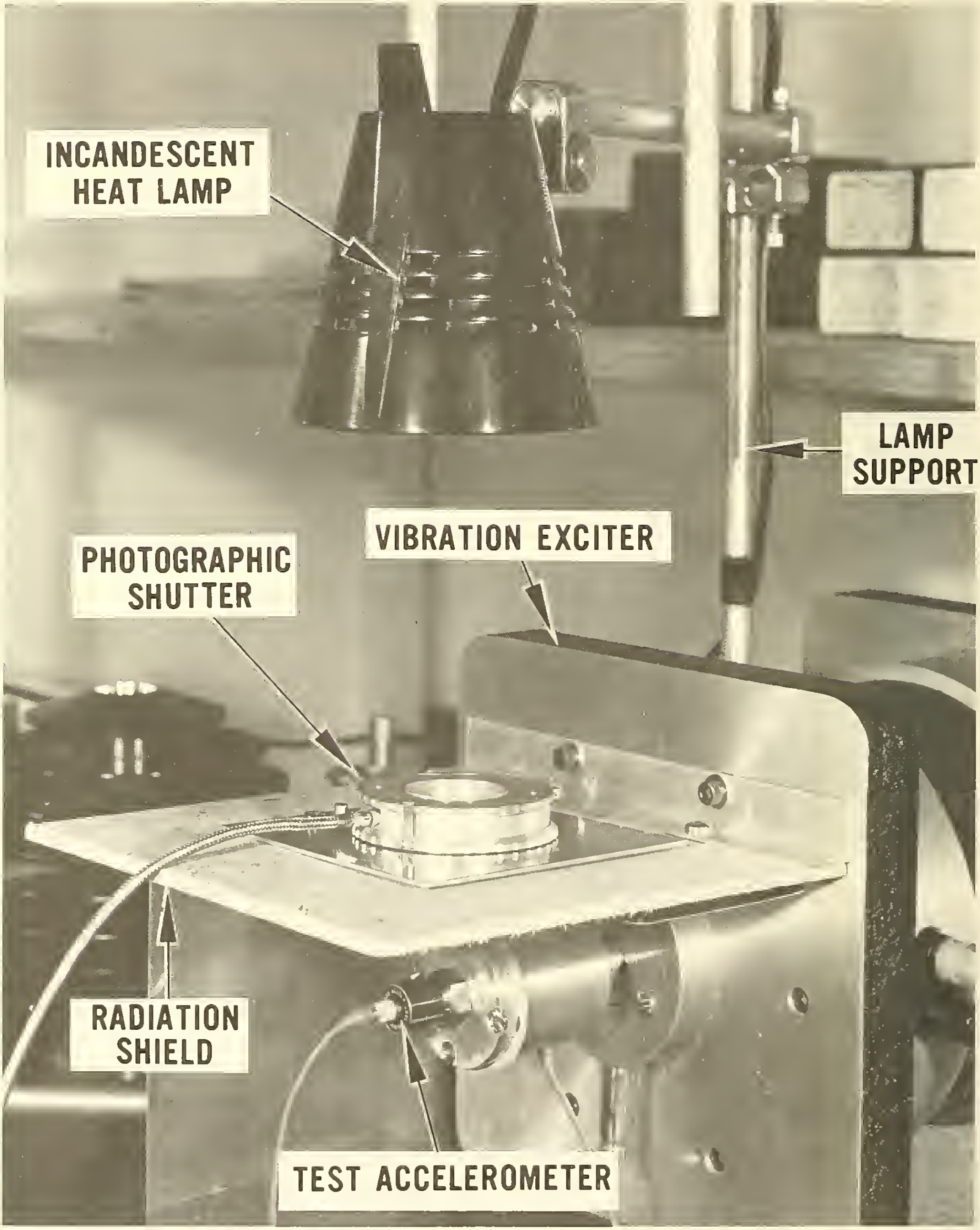


Figure 1. View of radiant heat lamp and shutter with test accelerometer side exposed to thermal transient.

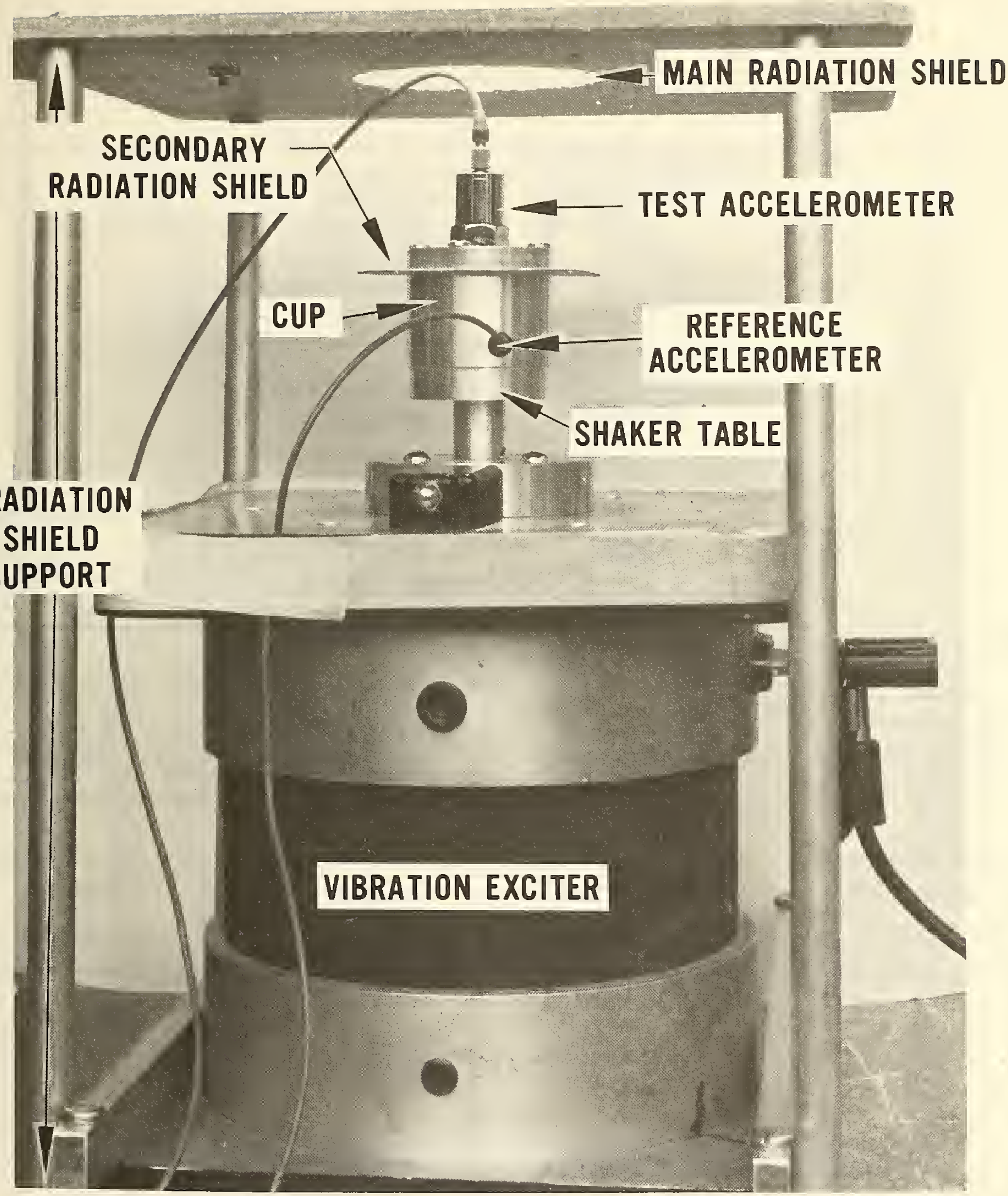


Figure 2. Test and reference accelerometers on vibration exciter.

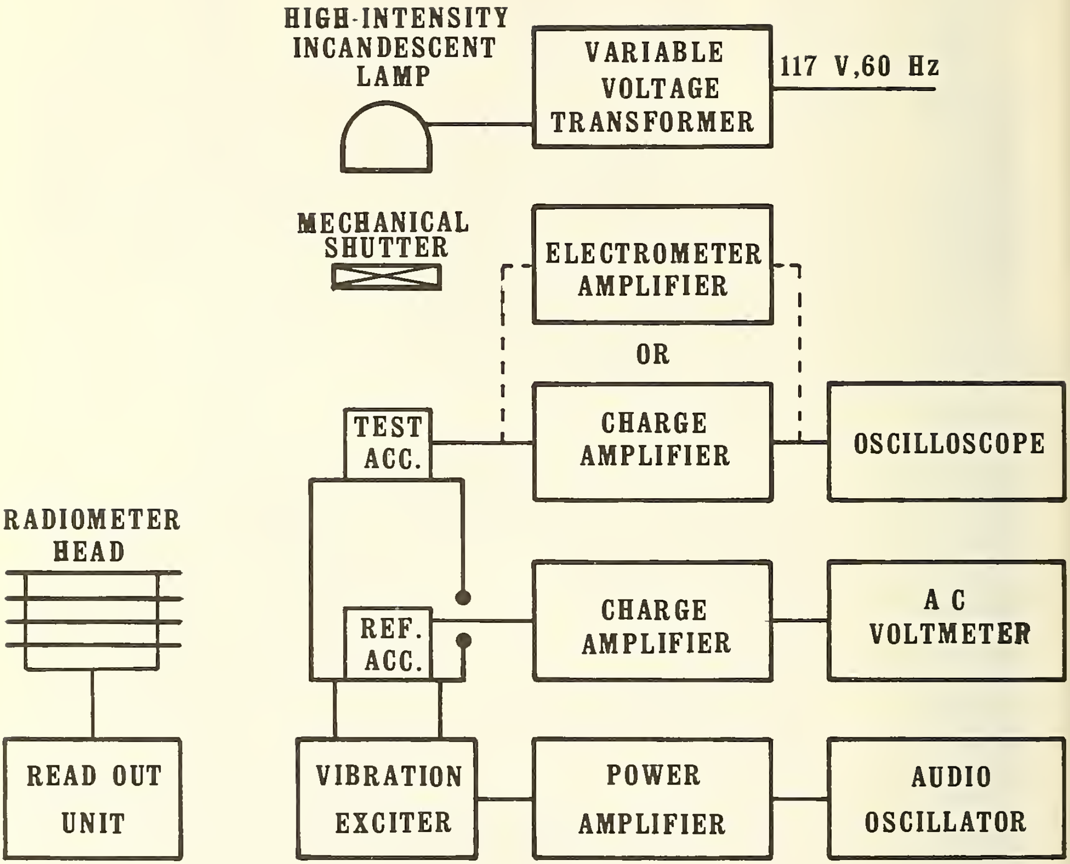


Figure 3. Block diagram of test equipment for thermal transient test on piezoelectric accelerometers.

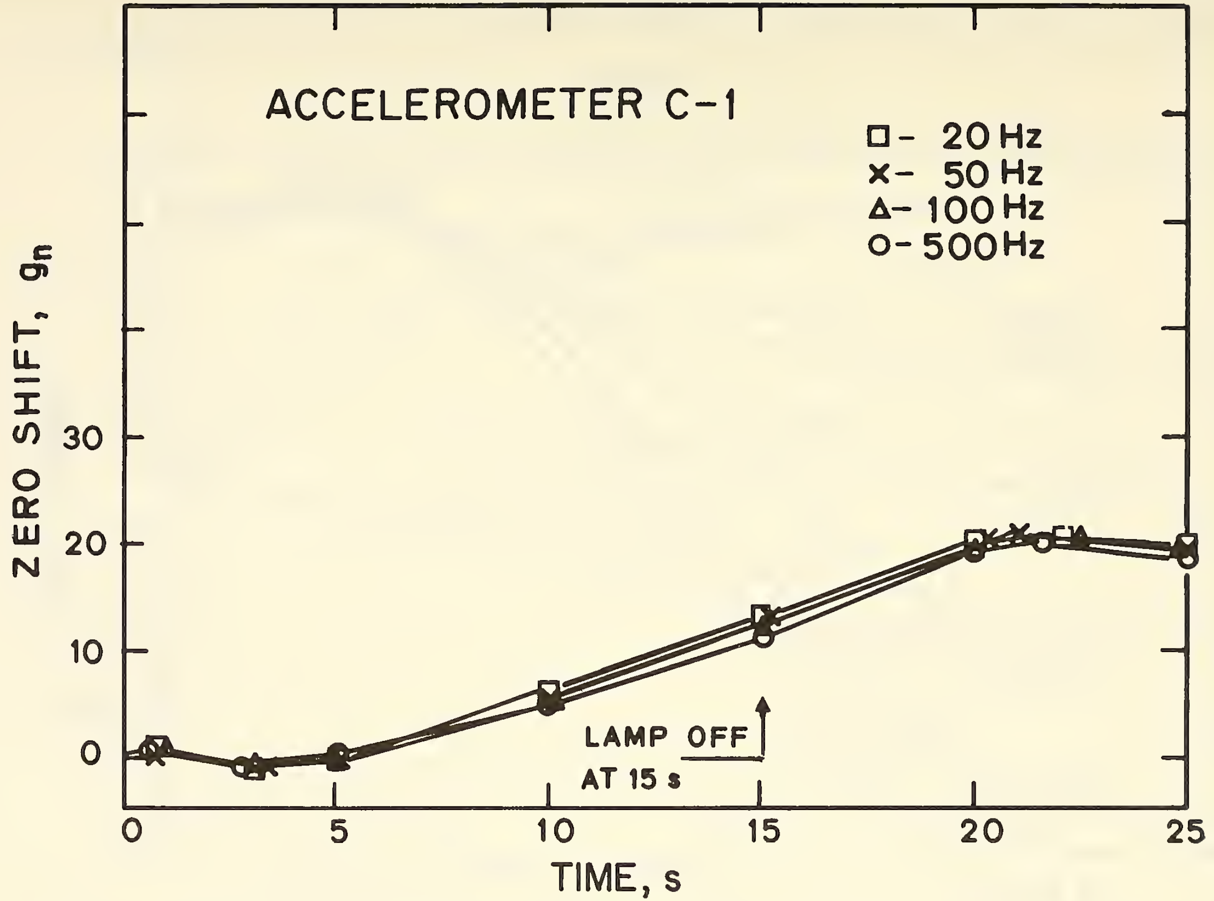


Figure 4. Accelerometer zero shift as a function of vibration frequency, 15 s exposure, 1 W radiation power level charge amplifier.

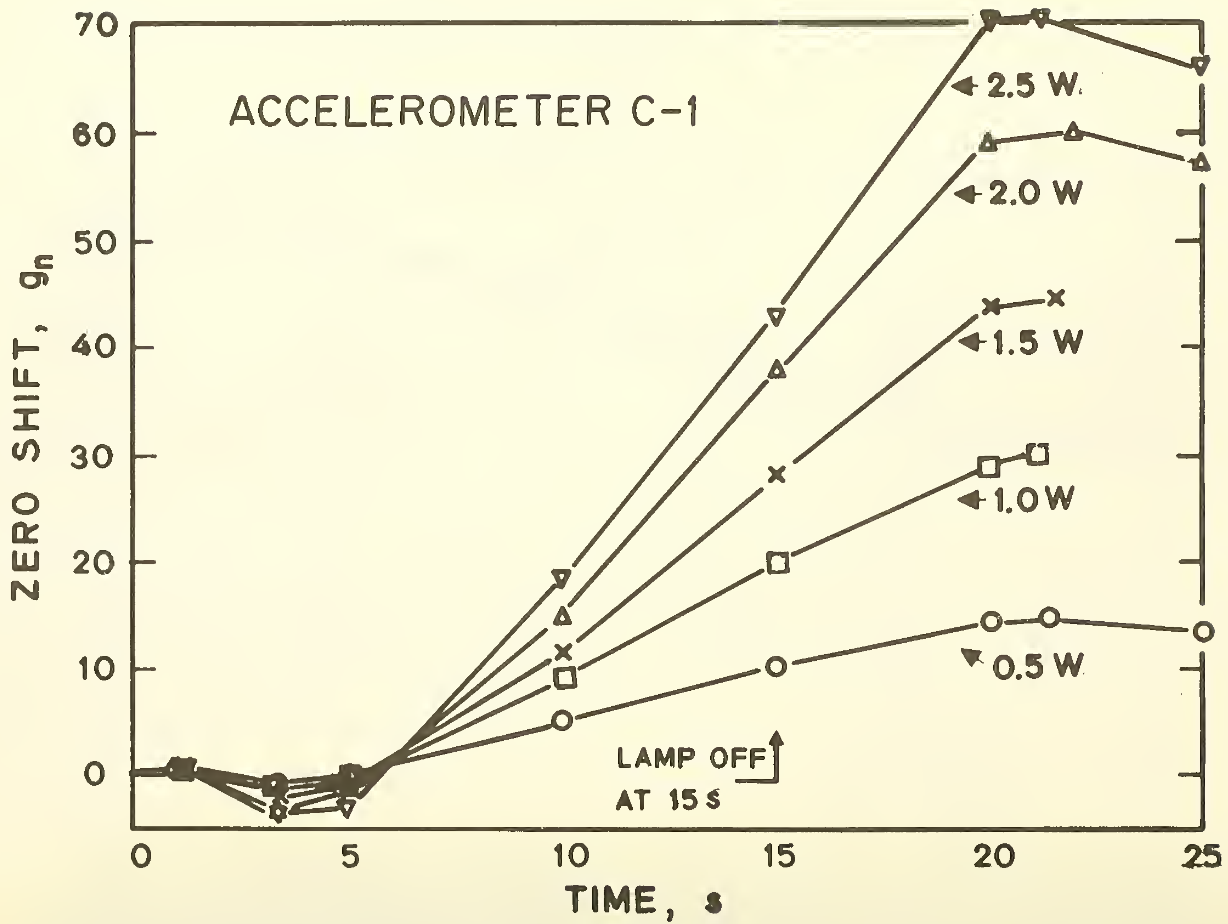


Figure 5. Accelerometer zero shift as a function of radiation power level, 15 s exposure, charg amplifier.

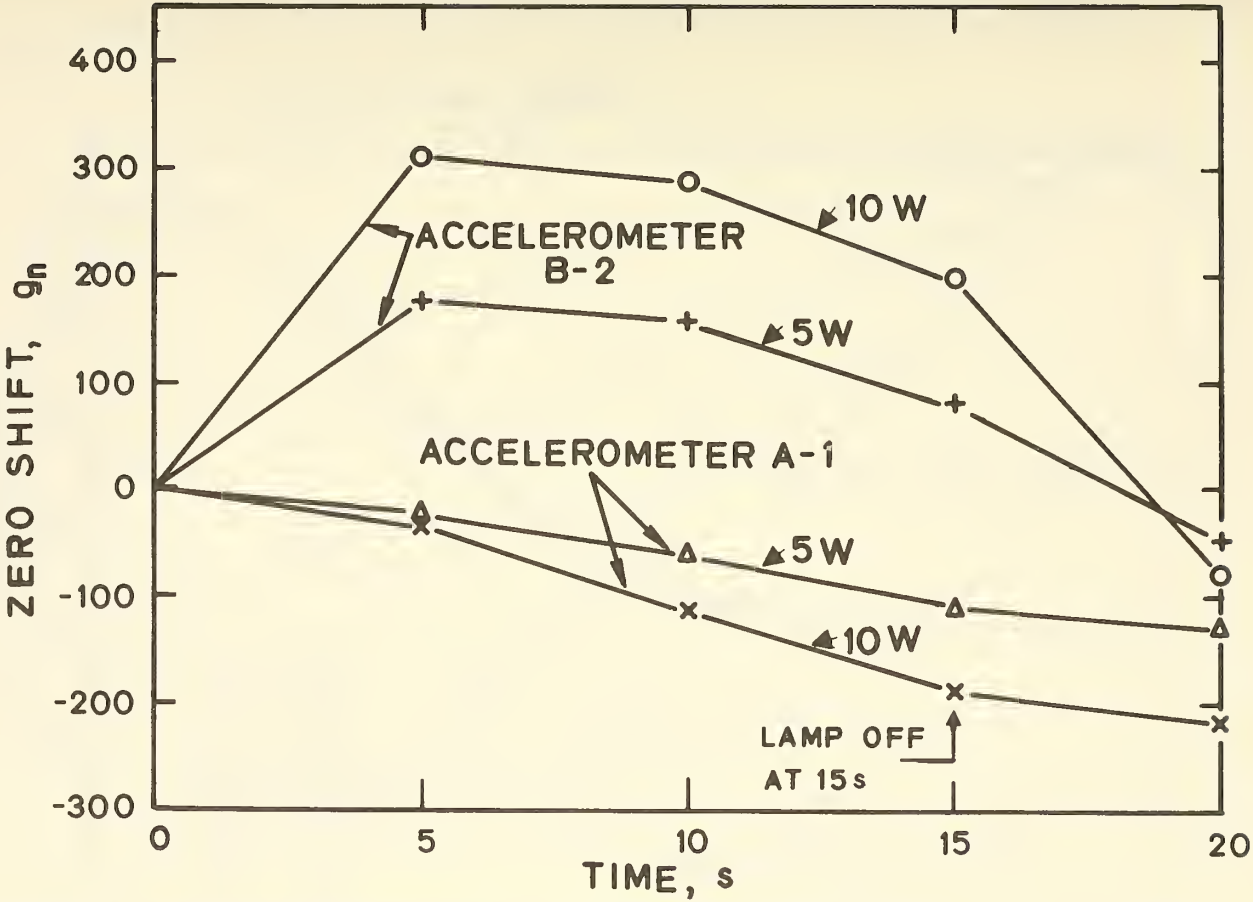


Figure 6. Accelerometer zero shift as a function of radiation power level, 15 x exposure, electrometer amplifier.

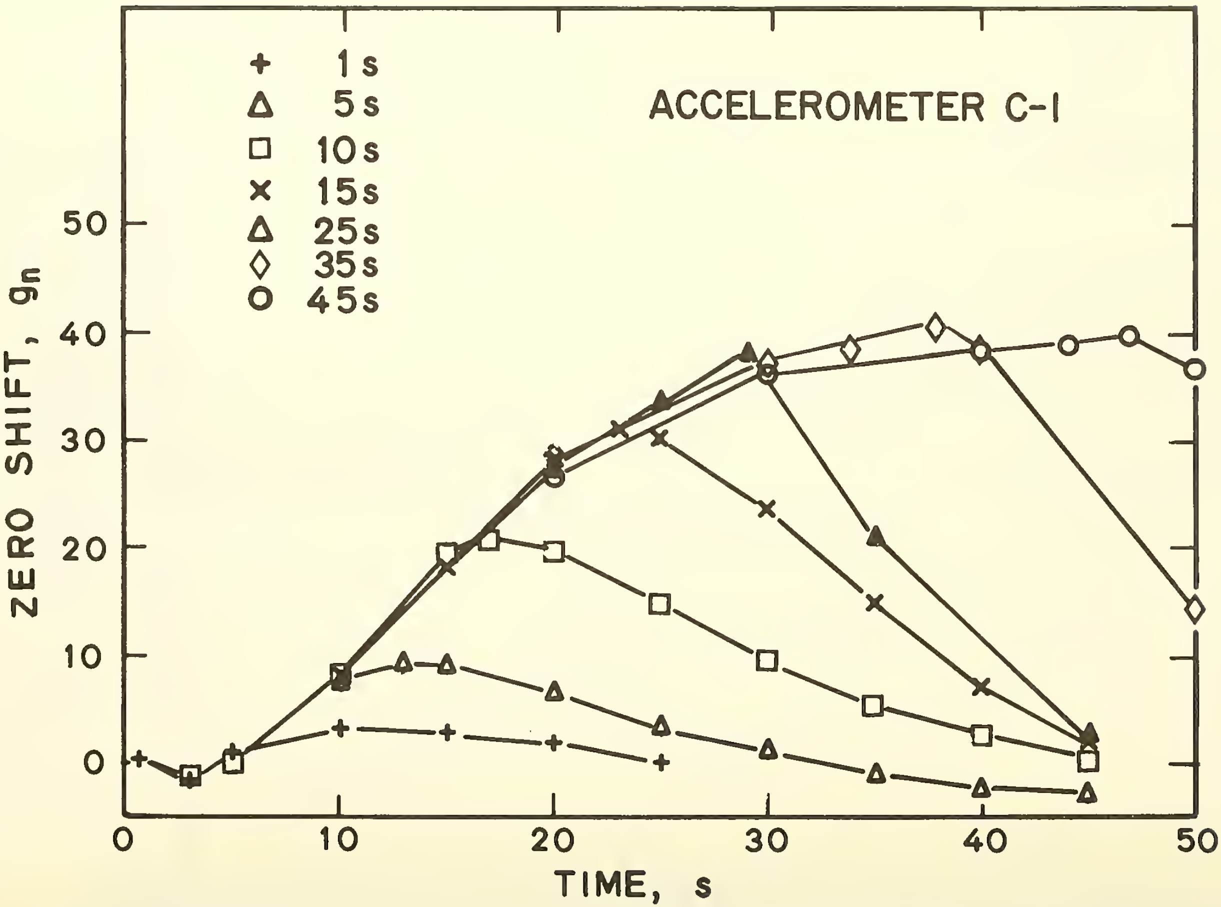


Figure 7. Accelerometer zero shift as a function of time from exposure initiation for various exposure times, 1 W radiation power level, charge amplifier.

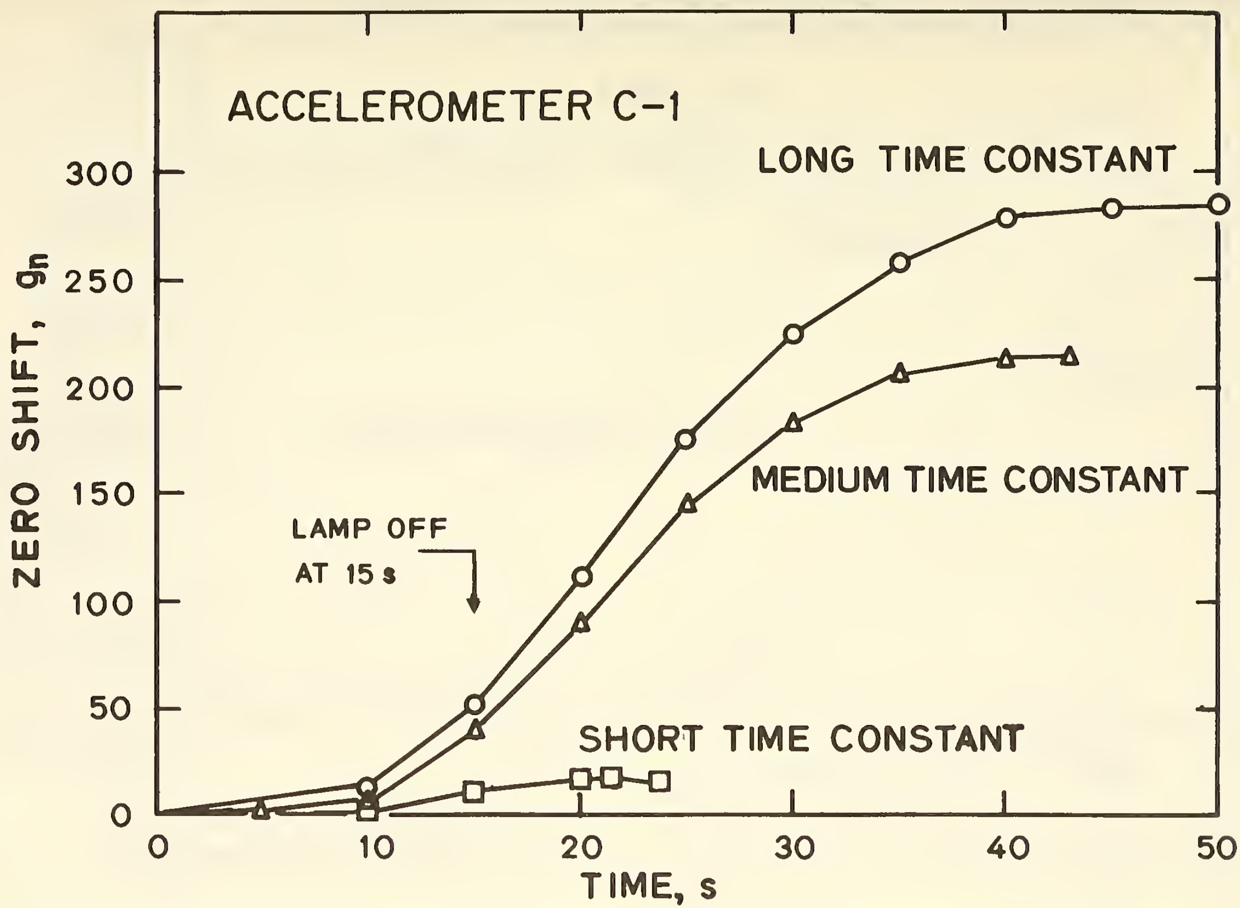


Figure 8. Accelerometer zero shift as a function of time constant, 1 W radiation power level, charge amplifier.

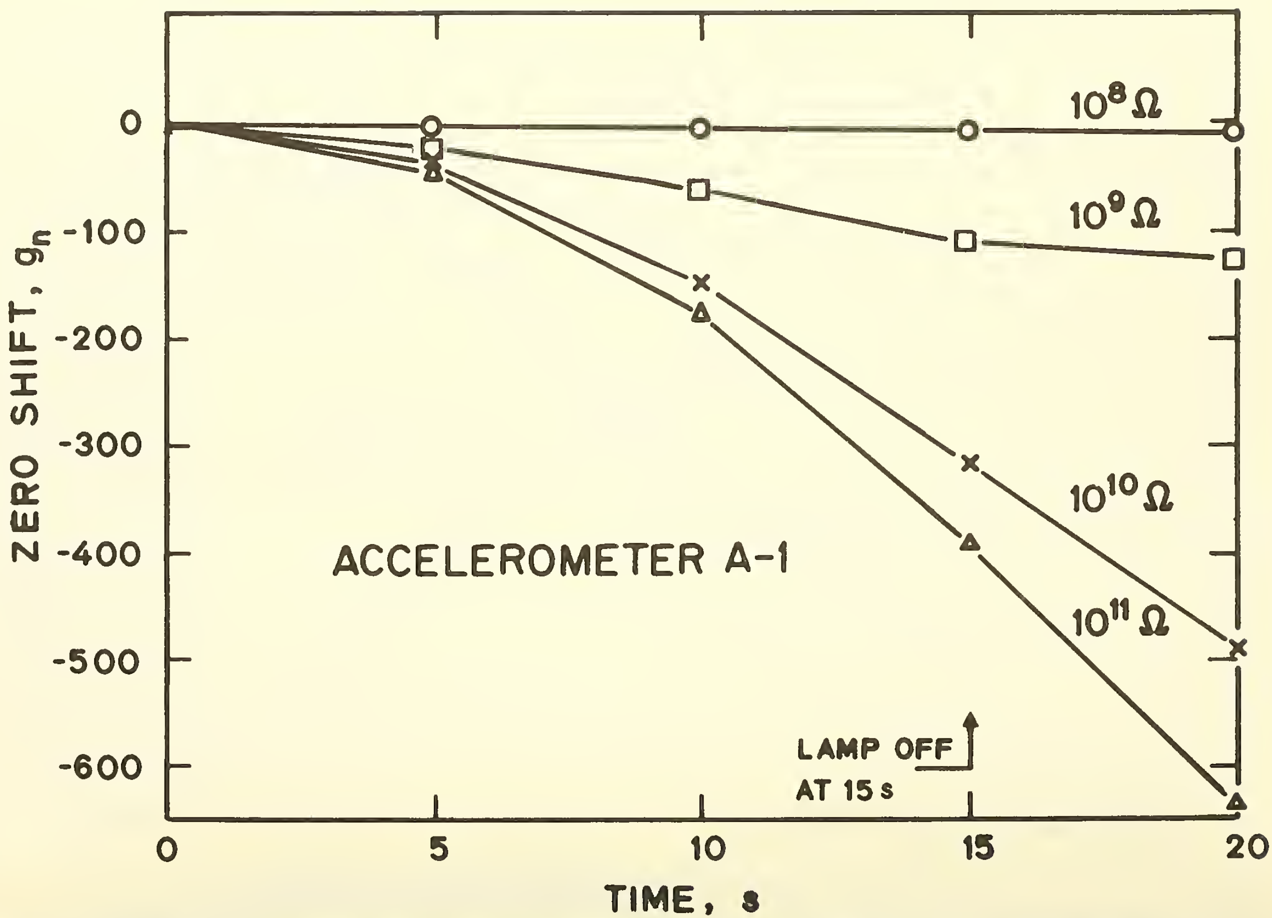


Figure 9. Accelerometer zero shift as a function of time for various values of electrometer input resistance, 5 W radiation power level.

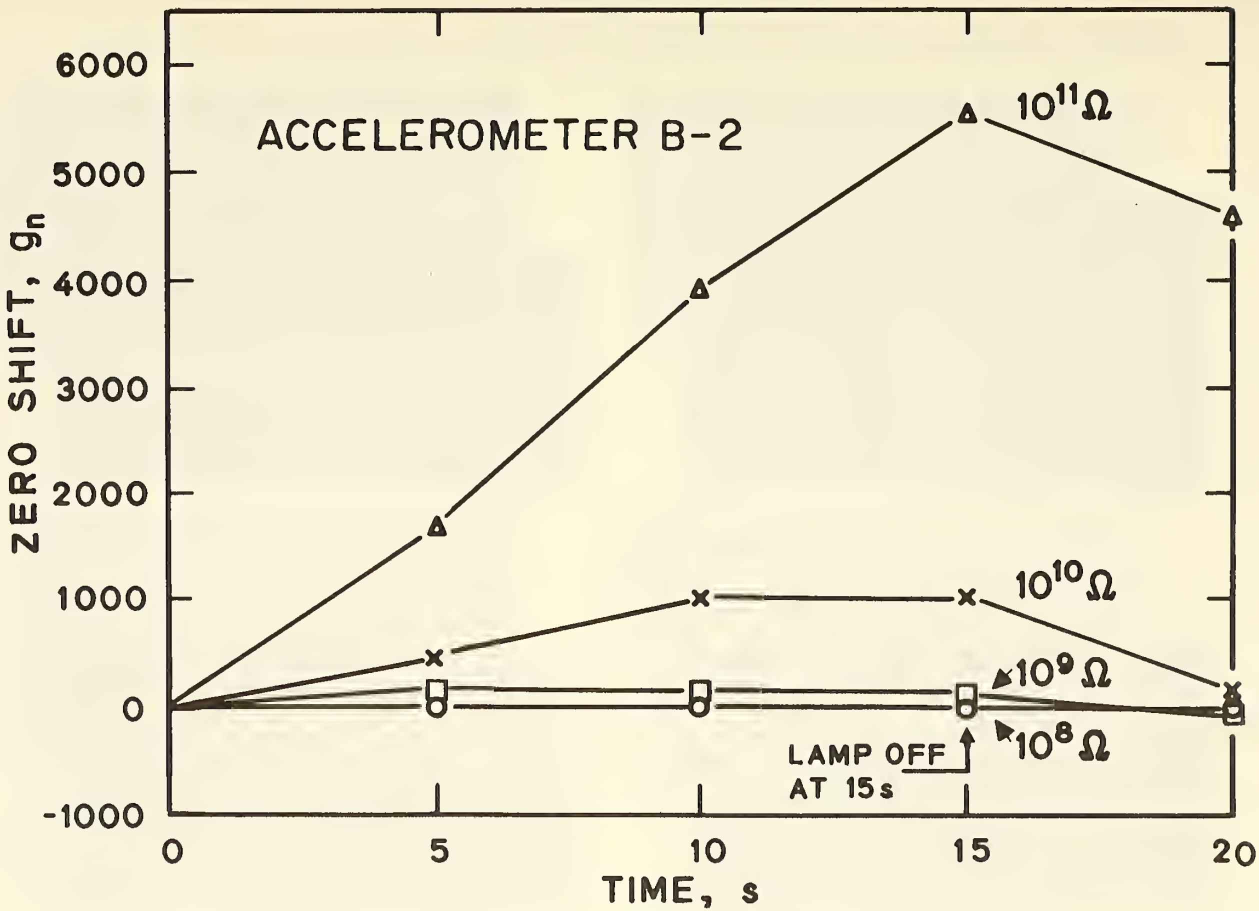
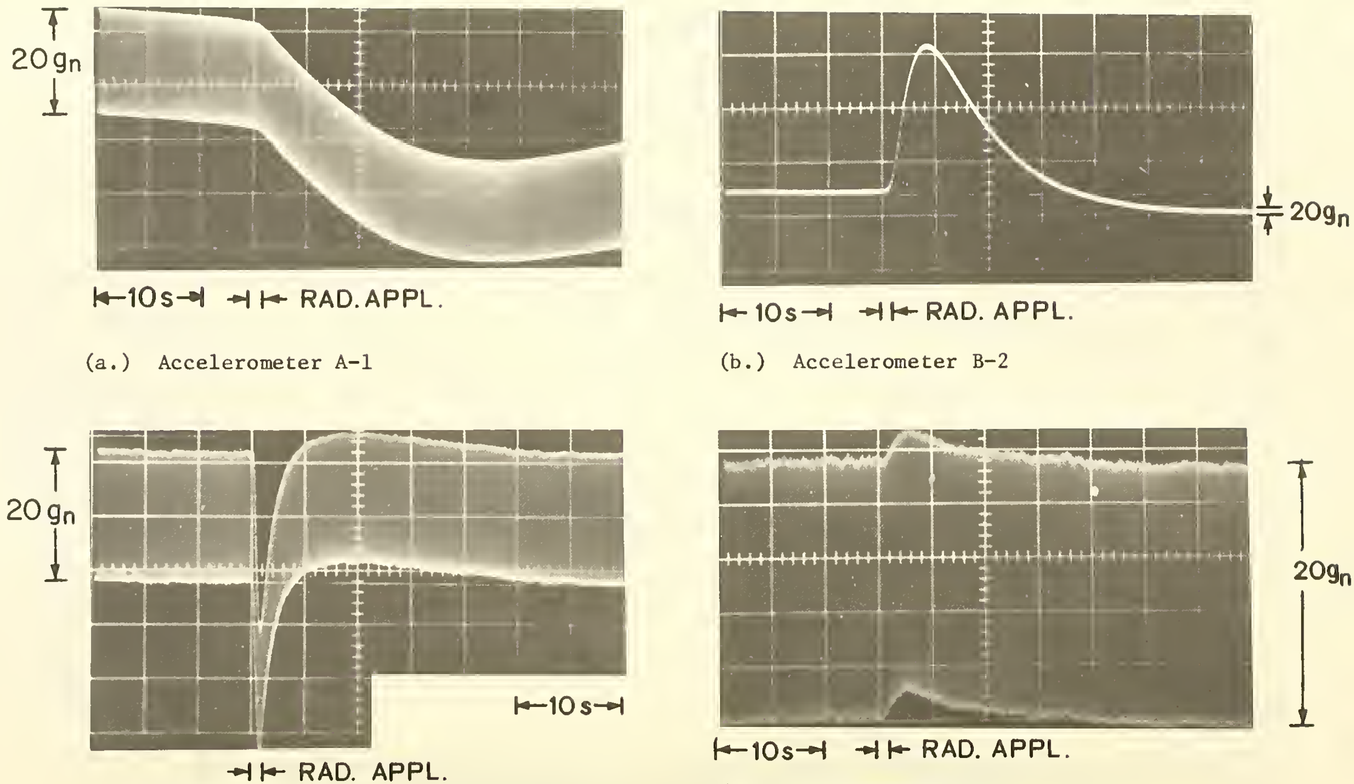


Figure 10. Accelerometer zero shift as a function of time for various values of electrometer input resistance. 5 W radiation power level.



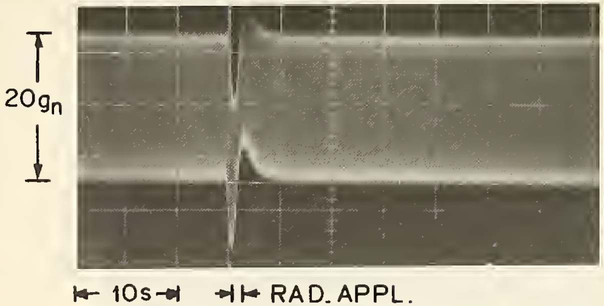
(a.) Accelerometer A-1

(b.) Accelerometer B-2

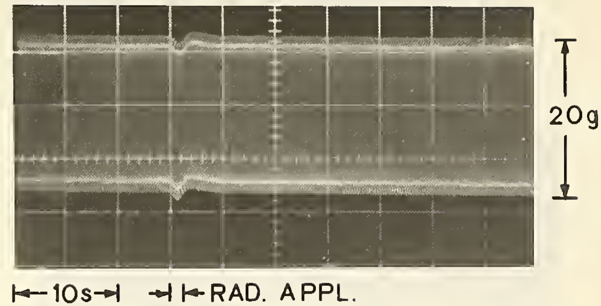
(c.) Accelerometer D-1

(d.) Accelerometer E-2

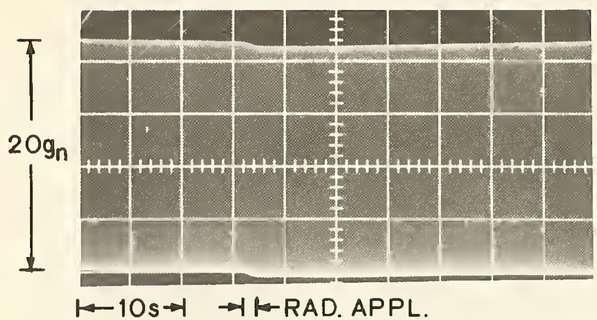
Figure 11. Representative outputs for 1-s exposure of accelerometer top, direct coupled charge amplifier.



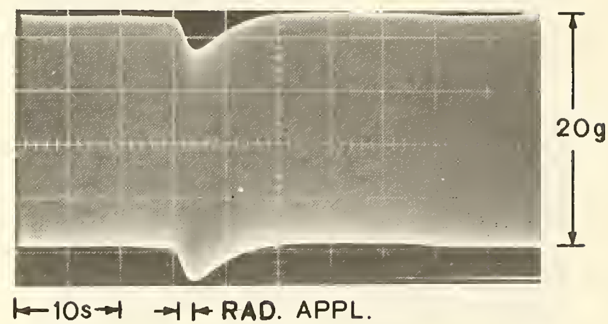
(a.) Accelerometer D-2; top surface irra-
diated



(b.) Accelerometer D-2; side irradiated;

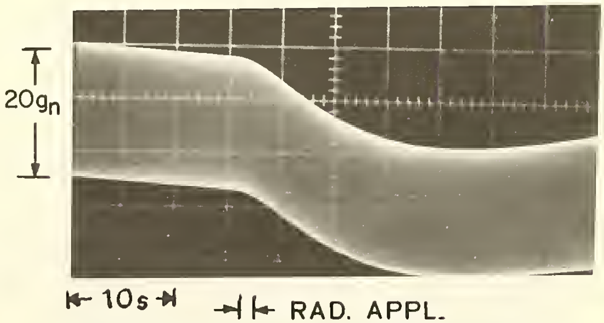


(c.) Accelerometer A-1; top surface irra-
diated

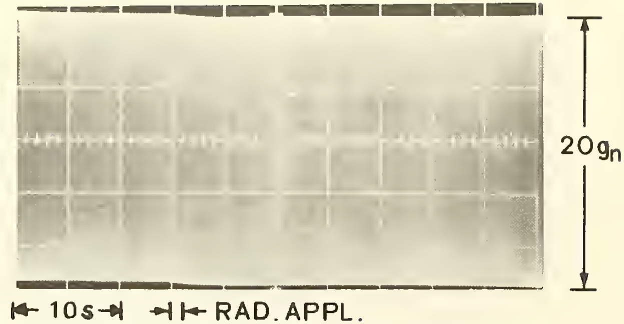


(d.) Accelerometer A-1; side irradiated;

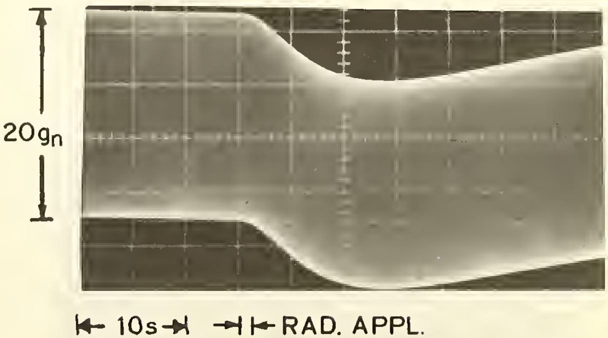
Figure 12. Comparison of exposure to thermal transient of side and top surfaces, 1-s exposure, electrometer amplifier coupled through filter.



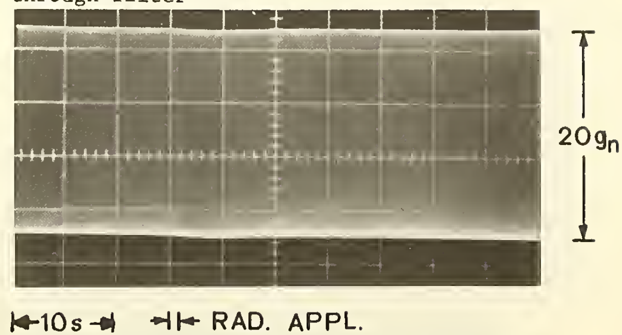
(a.) Accelerometer C-2; electrometer amplifier $10^{10}\Omega$ input resistance; direct coupling;



(b.) Accelerometer C-2; electrometer amplifier $10^{10}\Omega$ input resistance; coupling through filter

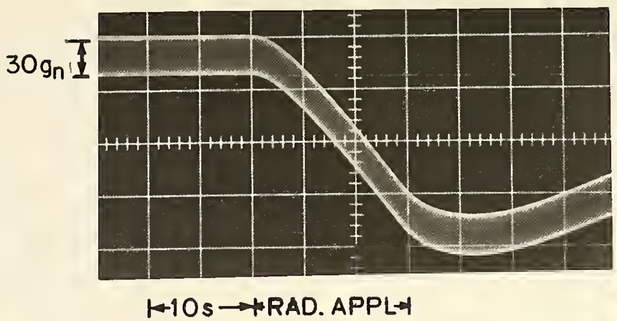


(c.) Accelerometer C-2; charge amplifier; direct coupling

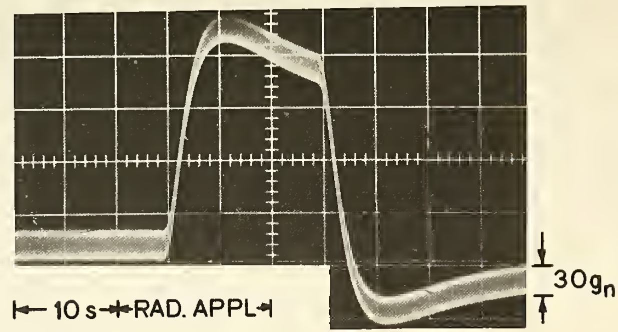


(d.) Accelerometer C-2; charge amplifier; coupling through filter

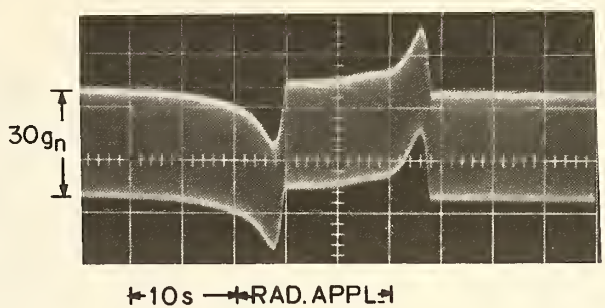
Figure 13. Accelerometer C-2 output using various circuit configurations, 1-s exposure of top surface.



(a.) Accelerometer A-1



(b.) Accelerometer B-2



(c.) Accelerometer D-2

(d.) Accelerometer E-2

Figure 14. Accelerometer outputs for 15-s exposure ot top surface, direct coupled electrometer amplier.

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16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

A simple, inexpensive method was developed for determining the effects of thermal transients on the zero output and sensitivity of piezoelectric accelerometers. Thermal transient stimuli are generated by an incandescent lamp and can be made to heat the top or side of the test accelerometer. Fourteen commercial accelerometers were tested using this technique. Zero shifts with magnitudes as high as 640 g_n^* were observed. Zero shifts up to 2% of full-scale resulted from one-second duration transients, and up to 7% of full-scale from fifteen-second transients. These results were obtained at a radiation power density of 1.8 W/cm^2. No changes of accelerometer sensitivity exceeding experimental uncertainties were noted as a result of the thermal transients used.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Accelerometer; performance characteristics; piezoelectric; test method; thermal radiation; thermal transient; zero shift.

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